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Environmental impacts of distributed energy systems—The case of micro cogeneration

Martin Pehnt *

Institute for Energy and Environmental Research Heidelberg, Wilckensstr. 3, D-69120 Heidelberg, Germany

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ABSTRACT

Distributed generation in micro cogeneration systems, e.g. reciprocating or Stirling engines and fuel cells, is of increasing interest in the energy market. This paper investigates environmental impacts of micro cogeneration by carrying out a detailed life cycle assessment and an analysis of local air quality impacts of micro cogeneration systems.

Most micro cogeneration systems are superior, as far as the reduction of GHG emissions is concerned, not only to average electricity and heat supply, but also to state-of-the art separate production of electricity in gas power plants and heat in condensing boilers. The GHG advantages of micro cogeneration plants are comparable to district heating with CHP. Under the assumption that gas condensing boilers are the competing heat-supply technology, all technologies are within a very narrow range. Looking at the GHG reduction potential on the level of a supply object (e.g. a single-family house) by modeling the operation with a CHP optimization tool, the achievable mitigation potential is somewhat lower, because the micro cogeneration systems do not supply the whole energy demand. Here, fuel cells offer the advantage of a higher power-to-heat ratio.

Environmental impacts other than those related to climate and resource protection relate more specifically to technology. In addition to investigating the emissions side, analysis of the air quality situation of a residential area supplied by reciprocating engines was carried out. The analysis shows that for the selected conditions, the additional emission of NO_x due to the engines do not create severe additional environmental impacts.

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1. Introduction

The electricity system in Europe is currently undergoing a process of transformation. Market deregulation has led to mergers and acquisitions in the electricity sector, but has also forced companies to seek out new business areas. Environmental regulations, like the Kyoto process and the European Emissions Trading Scheme, are exposing the sector to external pressure. New technologies, such as renewable energy technologies, combined heat and power (CHP) or "clean coal" technologies, are entering the market. In Germany, the nuclear phase-out and the decommissioning of outdated power plants will lead to a significant need for replacement of generation capacity. The need for replacement is an extremely important driving force for transformation, making conventional and new technologies compete for a role in the future energy supply.

One possible development path is decentralization of the electricity system. Distributed power generation in small, decentralized units could help to reduce emissions, save grid capacity and provide opportunities for renewable energy. It could be a constituent part of a more sustainable energy future. Broad implementation of distributed generation, however, would imply thorough structural change and require a surge in innovation.

* Tel.: +49 6221 4767 36.
E-mail address: martin.pehnt@ifeu.de.
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Micro CHP (combined heat and power production) or micro cogeneration is the simultaneous production of heat and power in a single building (Harrison and Redford, 2001) based on small energy conversion units. Whereas the EU CHP directive defines micro cogeneration as "a cogeneration unit with a maximum capacity below 50 kW_{el}", we restrict ourselves to systems with a capacity of less than 15 kW_{el}. The heat produced is used for space and water heating and possibly for cooling, the electricity is used within the building or fed into the grid.

A number of different conversion technologies have been developed for the application in the domestic sector. These include reciprocating engines, Stirling engines, low- and high-temperature fuel cells, micro gas turbines and various other technologies, such as organic Rankine cycle (ORC) machines, modified steam engines, thermo photovoltaics, thermoelectric devices, etc.

The mass market for micro CHP will be for the replacement of gas heating boilers. The chances for a broad diffusion of innovative micro CHP technologies depend significantly on their economic performance, the regulatory framework, but also on the future development of the overall heat demand. In the extreme case of very low-energy, passive houses, micro cogeneration is not useful at all. Whereas the exact determination of market volumes is not the scope of this paper, various market studies show that the existing building stock as well as less ambitious building standards leave ample potential for a large micro cogeneration market even though there are, of course, many competing options, including larger district heating, other renewable heat technologies, etc. (Krewitt et al., 2005).

It has often been argued that, due to its decentralized nature and high total efficiencies, cogeneration, and ultimately also micro cogeneration, contributes toward environmental relief. The present paper evaluates this assumption and investigates the potential environmental effects of a deployment of micro cogeneration on different levels, e.g. the power plant *operation*, the upstream environmental impacts of *fuel supply*, the environmental impacts of *power plant manufacturing and construction*, and of electricity and heat *distribution*. Special attention must be paid to the pollutant emissions which take place closer to the consumer due to the decentralized nature of the power plant conversion unit.

2. Life cycle assessment of micro cogeneration

To assess the impacts for the case of micro cogeneration, and to compare it to competing energy supply technologies, we use the methodology of *life cycle assessment* (LCA). The two key elements of LCA are:

- assessment of the total life cycle ("cradle-to-grave approach") of a given energy conversion technology, including the exploration, processing, transport of materials and fuels, the production and operation of the investigated energy conversion units, and their disposal/recycling, and
- assessment of different environmental impacts on resources, human health, and ecosystems.

An LCA basically consists of four steps: first, a *goal and scope definition* serves to describe the investigated product, the data sources and system boundaries, while defining the functional unit, i.e. the reference for all related in- and outputs. This functional unit could be, for instance, the provision of 1 kWh electricity to the customer or the supply of a hotel with heat and electricity for 1 year. Second, an *inventory analysis* "involves a data collection and calculation procedure to quantify relevant inputs and outputs" (ISO, 1997). Third, the potential impacts of the in- and outputs of the inventory analysis are determined by an *impact assessment*, which categorizes and aggregates the environmental interventions. For that purpose, environmental impact categories (labeled j), such as global warming, eutrophication, acidification, or summer smog are defined and characterization factors g_{ij} calculated (e.g. global warming potential) which describe the contribution of different substances e_i (e.g. CO_2, CH_4 or N_2O) to that particular impact category. The total environmental impact EI_j is then given by

$$EI_j = \sum_i g_{ij} \cdot e_i \quad (1)$$

Fourth, through *interpretation*, the findings from the inventory analysis and the impact assessment are combined in order to draw conclusions or formulate recommendations.

In the case of micro cogeneration, specific issues are associated with data uncertainty and forecasting, because many of these technologies are not yet fully developed (Pehnt, 2003). In addition, cogeneration is a technology path with joint or co-products, which have to be taken into account to obtain a full picture of the environmental consequences.

2.1. Considering the co-product

For the results of an LCA of cogeneration systems, the way that the co-product is considered turns out to be important. As cogeneration systems produce heat and electricity simultaneously, and the comparison to other, non-cogeneration systems often takes place based on the functional unit "1 kWh electricity" or "1 kWh heat", both products need to be taken into account together.

Let EI_j be the environmental impact of the production of 1 kWh_{el} plus the equivalent amount of heat in a cogeneration device (e.g. if the system has an electrical efficiency of $\eta_{el} = 0.3$ and a thermal efficiency of $\eta_{th} = 0.5$, the functional unit would be 1 kWh_{el} plus 1.67 kWh_{th}).

EI_j can be split up into a contribution which is directly caused by electricity production $EI_{j,\ \text{electricity direct}}$, a contribution which is directly caused by heat $EI_{j,\ \text{heat direct}}$ and a "base" contribution which cannot be directly causally attributed to heat or electricity production $EI_{j,\ \text{base}}$ (see Eq. (2)).

$$EI_j = EI_{j,\text{base}} + EI_{j,\text{electricity direct}} + EI_{j,\text{heat direct}} \quad (2)$$

Typically, $EI_{j,\ \text{base}}$ dominates the total result. An example for $EI_{j,\ \text{electricity direct}}$ is the environmental impacts from the production of a generator, whereas the supply of a fuel or the emissions from its combustion cannot be directly attributed to the production of heat or electricity and are thus part of $EI_{j,\ \text{base}}$.

The aim is to calculate the environmental impact of 1 kWh_{el} $EI_{j,\ electricity}$ without the co-product heat. There are several ways to deal with this problem. One is *allocation* of the environmental cost between the products with an appropriate key. The allocation factor $\gamma_{electricity}$ characterizes the share of $EI_{j,\ base}$ that should be accounted for in $EI_{j,\ electricity}$:

$$EI_{j,electricity} = \gamma_{electricity} \cdot EI_{j,base} + EI_{j,\ electricity\ direct} \quad (3)$$

For the case of a cogeneration system, one allocation key could be the energy generated. Take the example of an electric efficiency of 40% and a thermal efficiency of 40%. For each kWh electricity, 1 kWh heat is produced. The allocation key would thus be 0.5. That means that 50% of the, for instance, CO_2 emissions are related to the production of electricity and 50% to heat. However, this allocation key does not really characterize the value of the products. Instinctively, 1 kWh electricity seems more valuable than 1 kWh low-temperature heat. Therefore, often the *exergy* is used as the allocation basis (Menard et al., 1998). Exergy describes the amount of useful energy that is contained within a product. The exergy content of electricity $\zeta_{electricity}$ is equivalent to its energy (i.e. $\zeta_{electricity} = 1$), whereas the exergy of heat, in contrast, is given by the Carnot factor multiplied by the energy value (i.e. the exergy content of heat ζ_{heat} is

$$\zeta_{heat} = 1 - \frac{T_{ambient}}{(T_{supply} - T_{return})/(\ln(T_{supply}/T_{return}))}. \quad (4)$$

$\gamma_{electricity}$ would then be the quotient of electricity exergy and total exergy:

$$\gamma_{electricity} = \frac{\zeta_{electricity} \cdot \eta_{el}}{\zeta_{electricity} \cdot \eta_{el} + \zeta_{heat} \cdot \eta_{th}} \quad (5)$$

is the exergy content of electricity which is 1 (i.e. 1 kWh electricity corresponds to 1 kWh exergy) and

The second way to deal with co-products is to estimate the *avoided burden*. Thus,

$$EI_{j,electricity} = EI_j - EI_{j,heat(substituted\ systems)} \quad (6)$$

In the case of a micro cogeneration system example above, $EI_{j,\ heat(substituted\ systems)}$ would correspond to the environmental impacts from producing 1.6 kWh heat in a system that is likely to be substituted by micro cogeneration. This means that – if we want to compare micro cogeneration to other electrical power plants – we have to identify the heating systems that would actually be replaced by such systems. This depends on a number of factors, for instance the country, the type and age of the houses, the preferred fuels, and the like. It also depends on the perspective of the decision-maker: from the perspective of a politician who has to calculate CO_2 mitigation impacts of certain political measures, it is the individual, old heating system that might be superseded by a micro cogeneration system. Boiler manufacturers might think of micro cogeneration competing with other modern heating systems. A home owner who has to decide which heating system to install will have to consider, for instance, a micro cogeneration home energy system compared to a modern condensing boiler.

For the cogeneration systems investigated here, we choose the *avoided burden approach*, where the co-product is credited with an alternative generation route. This approach reflects most accurately real decision-making situations. Also, if we had chosen an allocation procedure, it would be necessary to compare micro cogeneration to other electricity *and* heat systems simultaneously.

We furthermore regard electricity as the main product, while generated heat is credited, and analyze the replacement of a gas condensing boiler by a variety of micro cogeneration systems. The question answered through this substitution perspective is: which environmental impacts do micro cogeneration systems have if we install them instead of a modern gas condensing boiler?

It should be kept in mind that this way of crediting is the most conservative way to assess micro cogeneration because from the overall impacts, the lowest impacts from the best system based on the same fuel are subtracted. The advantages of micro cogeneration, compared to central generation without it, increase significantly as soon as less modern technologies or fuels with higher carbon contents (e.g. heating oil) are considered as the substituted heat supply. However, such a perspective detracts from focusing on the comparison of various technologies using natural gas.

Which *electricity* system should the micro cogeneration systems be compared to? Again, this depends on the perspective of the decision-maker. To identify advantages and disadvantages in comparison to the status quo, the current electricity mix can be chosen as a benchmark. Generally, however, we need to take a dynamic, forward-looking perspective. In Germany, for instance, some 40 GW_{el} power plant capacity must be replaced by 2020. Micro cogeneration represents one alternative way to cover this demand for new capacity. Micro cogeneration should, therefore, be compared to modern marginal power plants that would typically be installed. In many cases, this will be a natural gas combined cycle (CC) power plant. This procedure is in accordance with the EU directive on cogeneration, which demands that

> each cogeneration unit shall be compared with the best available and economically justifiable technology for separate production of heat and electricity on the market in the year of construction of the cogeneration unit (EU, 2004).

In addition to such a marginal approach, we include the German electricity mix as additional information.

2.2. Input data and reference systems for micro cogeneration systems, fuels, and conventional power plants

The micro cogeneration systems investigated here include several fuel cell, Stirling, and reciprocating engine configurations. These are compared to larger cogeneration systems, such as a large reciprocating engine and a gas combined cycle plant both feeding district heating systems. As benchmarks for separate generation options, a gas combined cycle plant without cogeneration, a modern lignite power plant, and the future German electricity mix, as forecasted by Enquête (2002), are assessed.

The reference time of the comparison is the year 2010. We choose this base year because several of the micro cogeneration systems, namely the fuel cell, the very small reciprocating engine, and the Stirling engine, are not yet fully technologically mature. For these systems, we do not evaluate the status quo, but rather extrapolate the technical performance to the year 2010, to take into account further expected technological progress.

We restrict our LCA analysis to natural gas and fuel oil as fuel. Even though micro cogeneration can, in principle, be operated with other fuels, the greater part of the systems will be operated with natural gas. Furthermore, by 2010, renewable micro cogeneration systems, such as pellet Stirlings or biomass gasification/fuel cell units, are not yet likely to be mature. It is obvious, however, that with respect to greenhouse gas emissions, the use of renewable fuels would be preferable.

For the purpose of this research, life cycle data were obtained for various micro cogeneration and conventional systems from the system manufacturers and additional data sources. Where possible, operational data from field tests and larger samples of systems was used. However, under the micro cogeneration technologies, this was possible only in the case of the reciprocating engine. Here, several measurement campaigns of larger statistical quantities were used as data source. For fuel cells and Stirling engines which have not yet been produced and operated in statistically relevant amounts, measurements from individual systems could be employed.

The LCA data were then implemented using the material flow and life cycle program Umberto (www.umberto.de). This program calculates the impacts caused by the full life cycle of the micro cogeneration systems and carries out an impact assessment in accordance with the international standard ISO 14042.

The fuel cell LCAs are based on our analysis in Krewitt et al. (2004). The material LCAs used for the various technologies, such as catalyst materials (e.g. platinum group metals), building and structural materials (such as concrete and steel), and materials for the electrical equipment (copper, etc.) are mainly based on Pehnt (2002). The natural gas LCA, as modeled in Umberto, represents a standard import mix for Germany, extrapolated to the year 2010 (gas sources: Germany 13%, Netherlands 19%, Norway 33%, GUS 35%). Electricity and conventional heat production data are taken from the detailed bottom-up Umberto/IFEU database. The district heating systems are based on a detailed model, including heat losses depending on the heat density, the length and isolation of the distribution grid, etc.

To account for uncertainties regarding the actual course of future development, but also variations with respect to application, manufacturer, technology, and other parameters, error bars are used to show the bandwidth of results. These represent the bandwidth of expected total results of ''real-world'' systems. Parameters included in the bandwidth are discussed below with respect to representativeness and validity.

- *Thermal efficiencies* depend strongly on: the application context, e.g. on whether a condensing operation can be achieved; which return temperatures are possible; how many start/stop procedures are carried out; how many full load hours are possible, etc. In addition, it is important whether a condenser is applied to exploit the condensing heat of the exhaust gas. This can, in principle, be used in most micro cogeneration applications. Often, it is rather an economic than an environmental question whether this extra device is used or not. Condensing operations are included in the possible system designs investigated here (Table 1).
- The emission of NO_x particularly of reciprocating engines varies strongly, depending on the emission reduction concept used ($\lambda = 1$ or lean operation), manufacturer, operation mode (partial load operation, static or dynamic operation, etc.), age of the system, and maintenance interval. The latter two aspects are particularly important for reciprocating engines. The NO_x emissions of $\lambda = 1$ systems can vary by one order of magnitude, depending on whether the catalyst has been newly exchanged or not. Likewise, emissions are very sensitive towards the calibration of engine characteristics. Engines in lean operation typically show more stable, but somewhat higher, emission levels. For the small Stirling engine, e.g. the WhisperGen, higher NO_x emission factors are reported. However, it is assumed that future systems will show reduced emissions, comparable to conventional gas burners.
- There is still uncertainty with respect to the bandwidth of unburnt *methane (CH_4) emissions* from reciprocating engines. In the literature on engine CHP, emission factors from 20 to 500 mg per MJ fuel input can be found. A Danish study, for instance, states that ''compared to complete combustion, the global warming potential for gas engines was on average raised by 20% by the emission of unburned fuel'' (Kristensen et al., 2004). Due to the high global warming potential of CH_4 (the impact of 1 kg CH_4 corresponds to 23 kg CO_2), 500 mg methane per MJ fuel corresponds to some 150 g of CO_2 equivalent per kWh electricity produced; methane emissions thus have a significant impact on overall emissions. Here, we assume a bandwidth of 10–320 mg/MJ fuel input, with 100 mg/MJ as default value based on field tests of reciprocating engines (Senertec, 1992–2003). For fuel cells and Stirling engines, the emission factors are orders of magnitude lower.
- The condensing boiler as an ''avoided burden system'' is assumed to have an average efficiency of 97% (lower heating value). This figure is 7–10% points below the nameplate efficiencies and are based on a large number of systems investigated in a variety of studies (e.g. Heidt, 2002, Wolff et al., 2004). It has been shown that the potentially high efficiency obtainable from the condensing operation cannot always be achieved, particularly in the summer.
- The system boundary of the heat production is the feed-in into the heat distribution system.

2.3. *Impact assessment*

For an impact assessment, characterization factors are required so as to be able to calculate environmental interventions (such as greenhouse gas emissions or acidification) from emission factors. For this study, we take characterization factors in accord with standard LCA procedures (CML et al., 1992; UBA, 1995; Franke and Vogt, 2000; Giegrich and Detzel, 2000). Due to space limitations, we can only present results for two important selected impact categories here: the emission of greenhouse gases (GHG) and acidification. The first category

Table 1 – Input data for the LCA of micro cogeneration systems (time frame 2010)

Reference number	Micro CHP											Larger CHP		Central	
	Fuel cells		Reciprocating engines						Stirling			Reciprocating	CC	CC	Lignite
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	PEMFC	SOFC	1 kW	3–6 kW lean (high NO_x)	3–6 kW lean (high NO_x cond)	3–6 kW lean (low NO_x)	3–6 kW ($\lambda = 1$)	3–6 kW lean (fuel oil)	0.8 kW	3 kW	9.5 kW	50 kW			
Capacity (default)															
Electric (kW_{el})	4.7	1.0	1.0	5.5	5.5	5.0	4.7	5.3	0.8	3.0	9.5	50.0	100,000	600,000	1,000,000
Thermal (kW)	12.5	2.7	3.25	13.9	14.9	12.6	12.5	11.4	6.0	15.0	28.5	98	95,556	0	0
Efficiency (default)															
Electric (%)	32	32	20	25	25	25	25	28	10	15	24	30	45	58	42
Total (%)	85	85[a]	85	88	93	88	88	88	85	90	96	88[b]	88[b]		
Efficiency (min)															
Electric (%)	28	28	20	25	25	25	25		10	15	22	28	45	55	
Total (%)	80	80[a]	80	84	88	84	84		80	85	88	85[b]	80[b]		
Efficiency (max)															
Electric (%)	32	32	20	25	25	25	25		12	19	26	33	49		
Total (%)	90	90[a]	85	95	99	95	95		90	94	100	90[b]	88[b]		
NO_x emission															
Default (mg/Nm^3)	3	3	n.a.	300	300	135	125	2150	80	80	80	125	95		
Bandwidth (mg/Nm^3)	–	–	n.a.	70–400	70–400	60–200	50–400	n.a.	–	20–110	20–110	50–400	n.a.		
Economic lifetime	80,000 h or 15 years, whichever is lower														

Caution: Whereas efficiencies for systems 4–8, 12–15 are based on large numbers of realized systems in real-world operation, values for the remaining systems are based on system models and target values of the manufacturers for future real-world performance. Efficiencies are based on lower heating value. All efficiencies are seasonal. Lean: lean operation, cond: use of condenser.

[a] Plus hot stand-by loss.

[b] Plus distribution losses.

represents climate change mitigation effects, but also reflects the use of fossil resources, as the impact category is dominated by CO_2 emissions from fossil fuel use. The second assesses the contribution of local emissions of, for instance, NO_x, NH_3 and SO_2 to acidification. Structurally similar results could have been obtained for eutrophication, for example. A number of additional impact categories are included in the model but will not be reported here.

The results of these cradle-to-grave analyses will be described in the following sections. First of all, the contribution of micro cogeneration to climate change mitigation will be assessed (Section 3.1). Then emissions of pollutants are discussed in Section 3.2, followed by an assessment of local pollutant levels resulting from the emissions of these systems (Section 3.3), and ending with a comparison on the household level of individual operators of micro cogeneration (Section 3.4).

3. Results of the life cycle assessment

3.1. *Greenhouse gas emission reduction of natural gas micro cogeneration*

3.1.1. *Micro cogeneration versus central electricity production*

As far as the prevention of GHG emissions is concerned, micro cogeneration systems are superior not only to the average electricity supply mix in Germany, but also to efficient and state-of-the art separate production of electricity in gas operated power plants and heat in condensing boilers (Fig. 1). Compared to separate generation with a natural gas combined cycle plant (without cogeneration) and a natural gas condensing boiler, micro cogeneration reduces GHG emissions by between 8 and 44% (Table 2), with the exception of the small Stirling engine. With lower electrical efficiency, its GHG level lies above the one of a gas combined cycle plant. Similar reductions are achievable with respect to primary energy demand.

There is still some uncertainty about the achievable total average efficiency of fuel cell systems. Estimates for future domestic systems range between 80 and 90%, whereas today the systems are far from this value. When taking the lower bound of 80% total efficiency for fuel cells only, the achievable reduction for domestic fuel cell systems does not seem very high. However, one can also reverse the argument: based on natural gas as a fuel, domestic systems might reach the same CO_2 emissions as a modern gas combined cycle plant, even though the systems are a factor of 100,000 smaller.

The GHG emissions mainly stem from the use phase, i.e. the operation of the cogeneration system. More than 80% of the emissions come from the CO_2 emitted through the combustion of the natural gas. For all systems investigated, less than 1% of the GHG emissions are caused by the

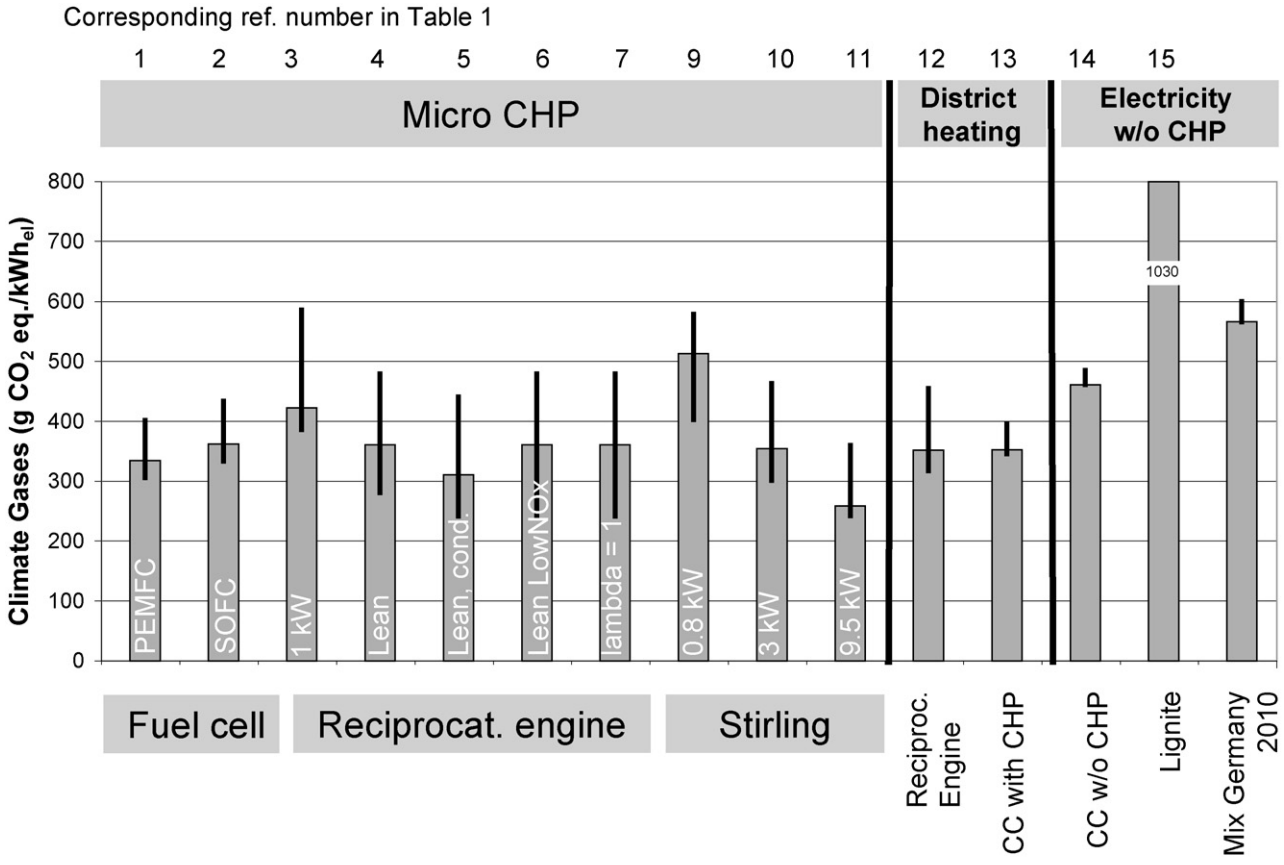

Fig. 1 – Life cycle GHG emissions of micro cogeneration technologies compared to large CHP and conventional electricity production in the year 2010; functional unit 1 kWh electricity at low voltage level, co-produced heat is credited ("avoided burden").

Table 2 – Reduction of greenhouse gas (GHG) emissions per kWh_{el} produced, achieved by micro cogeneration technologies with different baselines (combined cycle, anticipated German electricity mix in the year 2010, lignite power plant) and a heat credit based on a condensing boiler; shown are the values for the default cases in Table 1; fuel: natural gas

Technology status 2010	Ref. no. in Table 1	GHG reduction (heat credit:cond. boiler) compared to			
		Comb. Cycle w/o CHP	Comb. Cycle w/ CHP	Mix G 2010	Lignite
Fuel cell					
PEMFC	1	27%	5%	41%	67%
SOFC	2	21%	−3%	36%	65%
Reciprocating engine					
1 kW	3	8%	−20%	25%	59%
Lean	4	22%	−2%	36%	65%
Lean, condensor	5	33%	12%	45%	70%
Lean, low NO_x	6	22%	−2%	36%	65%
$\lambda = 1$	7	22%	−2%	36%	65%
Stirling engine					
0.8 kW	9	−11%	−46%	9%	50%
3 kW	10	23%	−1%	37%	65%
9.5 kW	11	44%	27%	54%	75%

Example: Production of electricity in a SOFC produces 36% less GHG emissions than the future German electricity mix when we assume that on the heat side, a gas condensing boiler is replaced.

production of the power plants. The remainder is emitted upstream through the supply and transport of the natural gas (e.g. CO_2 emissions from pipeline compressors and CH_4 from small leakages along the production path of the natural gas).

The reduction effects become greater when other fuels enter the comparison. With natural gas being a preferred fuel for micro cogeneration, it could be regarded as an enabling technology to replace other fuels such as heating oil in the heat market or coal in the electricity market. For instance, compared to separate production with more coal-dominated electricity mixes, such as the German electricity mix, or even compared to a lignite power plant, GHG reductions above 50% can be achieved. Note that the GHG emissions of the electricity mixes depend strongly on the fuel mix applied (for instance, France has, due to the high share of nuclear power, GHG emissions of around 100 g CO_2 equiv. per kWh_{el}, whereas the US of America have emissions around 740 g/kWh_{el} according to the database Gemis (2007)). Also, comparison with oil-fuelled boilers would lead to even higher GHG reductions. In such cases, the GHG reduction is to a great extent due to a fuel switch from higher carbon-containing fuels to natural gas. However, fuel switching is not restricted to cogeneration; its benefits could also be exploited with centralized, non-CHP production.

3.1.2. *Which is the best micro cogeneration technology?*

The determination of the best among the micro cogeneration technologies depends considerably on the efficiencies achieved. Under the assumption that gas condensing boilers are being substituted for, all technologies (fuel cells, reciprocating and Stirling engines) are within a very narrow range, with the exception of the small Stirling engine, which has lower electrical and overall efficiency. The high total efficiency of the large Stirling engine leads to the lowest GHG emissions. Fuel cells reach almost the same GHG emission level as the large Stirling when they achieve a total conversion efficiency of 90%. However, their thermal management is more complex, and the heat sources inside the fuel cell system are diffused. This makes it more difficult to harvest the heat co-produced in the system than, for instance, in a Stirling or reciprocating engine.

Fig. 1 also unveils large variations in GHG emissions for each system. These are particularly caused by varying thermal efficiencies, which depend on a system's context (e.g. return temperatures) and configuration. In addition, for reciprocating engines, the values for methane emissions due to unburned natural gas vary considerably. Therefore, the error bar for this technology is larger. Further research and measurements are needed in this area.

3.1.3. *Small versus large CHP*

The comparison between the different sizes of CHP reveals that micro cogeneration leads to GHG emissions on a level similar to district heat cogeneration. Whereas the electrical efficiencies of large plants are generally higher than those of smaller units, the total efficiency of large plants is not in general higher than that of the small systems. In addition, heat distribution losses for the district heating systems and electricity distribution losses in the case of large combined cycle (CC) plants have to be taken into account. Whether large or small CHP is favorable, therefore, depends on the specific situation under investigation.

In any case, district heating systems are not only an efficient way of realizing CHP, but also offer the possibility of a straightforward integration of renewable energy carriers, such as biomass or solar thermal energy, into the heat supply.

3.2. *Pollutant emissions*

It is not only climate change that is an issue of current environmental policy efforts. More generally, the protection of human health and the environment is in focus. In Europe, Directive 2001/81/EC on national emission ceilings for certain atmospheric pollutants, the so-called NEC directive, controls the reduction of sulfur dioxide (SO_2), nitrogen oxides (NO_x),

volatile organic compounds, and ammonia (NH_3). The aim is to combat impacts such as acidification, eutrophication, and ground-level ozone. This is to be achieved by limiting annual national emissions so that they do not exceed a ceiling laid down in the annex of the directive. Germany, for instance, is required to further reduce NO_x emissions in the year 2010 by 22% compared to the year 2000. Even this emission reduction, according to the German Advisory Council on the Environment, will not be sufficient to meet the long-term goals of the NEC directive.

Even though the low level of ambition of the directive is criticized by many institutions, scenario calculations show that many countries will not even be able to comply with its soft ceilings. According to the European Topic Centre on Air and Climate Change, the main problems foreseen by countries relate to the emission of NO_x (ETC-ACC, 2004). In the past few decades, emissions of NO_x have generally decreased significantly, particularly due to measures taken regarding power plants and vehicles. In the recent past, however, the *rate* of reduction has decreased significantly, too.

It is common to all gas-based power plants that the emission of SO_2 is almost completely avoided. Also, in gas-based micro cogeneration and other power plant technologies, the contribution of ammonia to, e.g. acidification, is almost negligible. Therefore, of all exhaust emissions by micro cogeneration systems, NO_x is of particular ecological importance in the context of the NEC directive. Nitrogen oxides are formed during the combustion process in most of the micro cogeneration technologies and contribute to many environmental impact categories, such as acidification, human health impairment, and eutrophication. Furthermore, NO_x assists in the formation of ozone and thereby contributes to summer smog and global warming; it also is a precursor material for the formation of small particles.

Whereas the total efficiencies of micro cogeneration technologies are similar, the various technologies differ considerably with respect to their emissions, particularly of NO_x. Reciprocating engines, which are based on discontinuous combustion at high-temperatures, exhibit the highest emission factors. Stirling engines, due to their continuous combustion and the possibility of applying modern burner technology (such as flameless oxidation burners), lead to very low emission factors. This is also true for fuel cells, due to the electrochemical nature of their combustion, the comparatively low-temperatures involved in the reforming reaction, and the requirement to clean up impurities such as sulfur and CO (PEFC). The direct NO_x emission factors for the operation of micro cogeneration systems, as derived from analysis of existing technologies and field tests, are given in Table 1.

In the following, we will concentrate on acidification as an important impact category, mirroring particularly the differences with respect to NO_x emissions of micro cogeneration technologies and, when compared, for example, to coal power plants, SO_2 emissions.

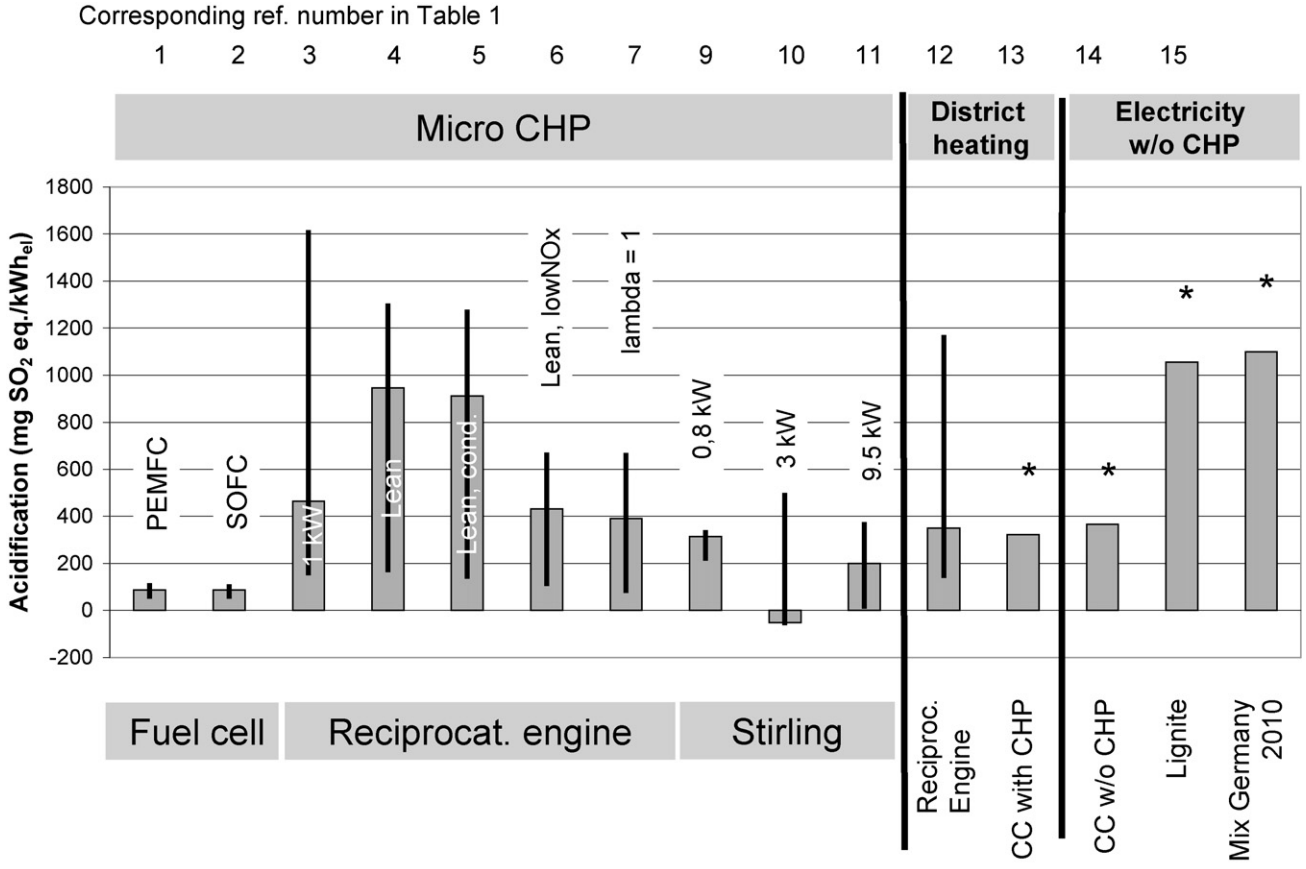

Fig. 2 – Life cycle assessment of acidifying emissions (NO_x, SO_2, NH_3) of micro cogeneration technologies compared to large CHP and conventional electricity production without CHP. *No data for bandwidth available.

In Germany, micro cogeneration systems have to be "state-of-the-art" in terms of pollutant emissions. This standard is regulated by the administrative instruction "TA-Luft"; the values of the TA Luft will be easily fulfilled by all micro cogeneration systems (Table 1). However, in some other European regions, emission legislation is much stricter than in Germany with respect to small CHP.

Fig. 2 displays the results of the life cycle assessment of the micro cogeneration technologies for acidification. It shows that fuel cells offer great advantages with respect to environmental impacts that are caused by local pollutants, such as acidification (mainly due to NO_x and SO_2). This also holds for other impact categories not shown in the figure. Unlike engine CHP plants, fuel cells couple the advantages of reduced energy consumption with low direct emissions. The remaining acidifying emissions stem mainly from their natural gas operating supply and, to a much lower degree, from system production (for the PEMFC, 13% of the total life cycle emissions stem from system production, for the SOFC 9%).

Similar advantages can be achieved by means of Stirling engines, which have very low direct emission factors as well, at least in the case of the innovative FLOX burner. For the small Stirling engine, we assumed that NO_x emissions of 80 mg/Nm^3 will be achieved in future systems from high-volume production.

Acidifying emissions from small reciprocating engines (considering the heat co-product) are somewhat higher than those of centralized gas power plants, due to more efficient emission control in large power plants.

3.3. *Local impacts from air pollutant releases*

When interpreting the LCA results for pollutant emissions, it is equally important to evaluate the impact of these emissions on the recipients side: how does the *local air quality* change due to the emissions? To address this question, the environmental relevance of the additional NO_x emissions of reciprocating engines will be assessed. For this purpose, a dispersion calculation for a virtual residential area was carried out, based on the software package AUSTAL 2000 (AUSTAL2000, 2003). For this calculation, it was assumed that, in a residential area based on multi-family residences, one third of the houses would be equipped with a reciprocating engine. This corresponds to 100 systems in a 1 km^2 area. In addition, avoided air pollutant releases due to the substitution of an alternative gas heating system are accounted for.

With respect to technical parameters, we conservatively assumed 5000 h of full load operation per year, an NO_x emission factor of 300 mg/Nm^3 (expressed as NO_2, see Table 1), and a share of 10% NO_2 of primary NO_x emissions. This latter assumption is of great importance, because NO_2 is of primary environmental concern. A site with flat topography with relatively critical weather conditions was selected: non-uniform wind distribution, large share of stable weather situations, and low wind speed that tend to lower the dispersion of pollutants. The surface texture corresponds to that of an urban area.

The results of this calculation show that the annual average concentration of NO_2 in the residential area due to net emissions from reciprocating engines is increased by 0.6 μg/m^3. This can be compared to the permissible level for the annual average NO_2 concentration; the German limit being 40 μg/m^3. The air concentration associated with the installation of the 100 units is thus very low—below a level of irrelevance, which is by German law defined as 1.2 μg/m^3.

In addition, the maximum short-term concentrations of NO_2 in air (i.e. not to be exceeded in more than 18 h) are generally below 7 μg/m^3, compared to the allowable level which by German law is 200 μg/m^3.

With respect to the impact on ambient air quality, reciprocating engines are not critical under the given circumstances. It has to be reiterated, however, that a flat topography was chosen for this analysis. Complex terrain (e.g. a narrow valley) might cause higher pollutant concentrations in certain places as calculated here. In addition, CHP systems based on heating oil contribute significantly higher NO_x emissions.

From a national perspective, of course, every measure to reduce NO_x emissions is welcome. This is why, from our perspective, low-NO_x reciprocating engines should be further developed and marketed. The market leader, Senertec, for instance, offers a high- and a low-NO_x system. The specific capital cost of the latter is approximately 10% higher. Thus, only 4–5% of the Dachs systems sold belong to the low-NO_x class.

3.4. *From specific impacts to supply objects*

In the preceding sections, we have analyzed the environmental impacts per unit of electricity or heat produced, i.e. we have looked at the *specific* impacts. In addition, it is instructive to investigate the impacts per *supply object*, e.g. per single-family house, per apartment house, per hotel, etc. The question we want to answer here is: how much environmental impact reduction can be realized in concrete supply objects with concrete micro cogeneration systems? To answer this question, the specific environmental impacts (per kWh energy supplied) are multiplied by different full load hours, giving the annual environmental impacts.

This analysis involves a further step: we need to analyze the amount of electricity and heat produced by the CHP unit, depending on the object and the CHP system (size, partial load characteristics, etc.). We can build on the results of a former investigation (Krewitt et al., 2004) where detailed modeling of the different supply objects based on time-resolved demand curves for heat and electricity and the techno-economic properties of the systems were carried out using the software BHKW-Plan (2004). This study delivers the full load hours, the share of own electricity consumption and grid electricity, the amount of heat produced in the peak boiler, etc. As the technologies were defined identically, we can directly use those results for further calculations.

It is important to note that the used calculations are based on real available or planned systems. For instance, the calculations for a single-family house utilize an 850 W Stirling engine (like the WhispherGen licensed by WhisperTech), a 1 kW solid oxide fuel cell (like the Hexis system) or a 1 kW reciprocating engine (Honda) (Table 3). The differing efficiencies and power-to-heat ratios also imply different full load hours.

Table 3 – Investigated technologies for the LCA of supply objects

	Reciprocating engine	Stirling engine	Fuel cell	District heating
Technologies				
Single-family (low)	1 kW	850 W	1 kW SOFC	20 kW rec. eng. w/ 17.8% heat loss
Multi-family (average)	5.5 kW	3 and 9.5 kW	4.7 kW	50 kW rec. eng. w/ 2.4% heat loss
Hotel	5.5 kW	3 and 9.5 kW	4.7 kW	
Full load hours (h/a)				
Single-family (low)	3373	1940	4786	4800
Multi-family (average)	5526–5639	5509–4160[a]	6432	6456
Hotel	5555–5730	5505–3939[a]	7015	–
Share of electricity produced in CHP (%)				
Single-family (low)	29	13	41	39
Multi-family (average)	24	13–31[a]	24	17
Hotel	26	14–31[a]	24	17
Share of heat produced in CHP (%)				
Single-family (low)	95	100	68	62
Multi-family (average)	61–65	65–93[a]	39	30
Hotel	65–68	68–92[a]	45	–

[a] First value: small Stirling, second value: large Stirling.

We have chosen this approach because it provides additional information; we cannot only estimate the impact reduction per supply object, but also how well a particular system fits the need of a supply object.

Beside the LCA of the specific impacts (per kWh) of each CHP unit, which were derived in the preceding sections, we need to model the energy flows of our supply objects. Therefore, for each object, we need to include the following information:

- The net electricity demand of the supply object. The supply object may require additional electricity, and the CHP unit may also feed electricity into the grid. We assume that the substituted electricity and the electricity fed into the grid have the same ''quality''. This is, to a certain extent, a simplification because micro cogeneration systems are very often thermally led; the electricity production of micro cogeneration units is therefore at maximum in periods of high space-heating demand, which are often also times of high electricity demand. Therefore, micro cogeneration might avoid the need for electricity production from environmentally more problematic peak load power plants. Assuming the identical quality of grid electricity bought by the supply object and of electricity fed into the grid, we therefore calculate a net electricity demand. It can be either positive, if less electricity is sold to the grid than bought, or negative, if more electricity is fed into the grid than bought.
- The CHP unit does not cover the full thermal load of the object. Therefore, peak load demand is considered to be covered by a modern gas condensing boiler.

This supply combination of micro cogeneration, grid electricity, and condensing boiler can then be compared to the reference, which assumes 100% coverage of electricity demand via the German electricity mix from the grid and heat demand from a condensing boiler. Again, our reference time is 2010. The functional unit for this type of analysis is the supply of an object with heat and electricity for 1 year.

The results of this analysis for the impact categories GHGs and acidification are shown in Figs. 3 and 4. In all cases, the default technology assumptions listed in Table 1 are used for the assessment. Several important conclusions can be drawn based on this analysis:

- Unsurprisingly, the advantages of the individual technologies, as assessed in Section 3.1, are mirrored in this analysis. This means that CHP technologies offer climate advantages, the fuel cell offers additional acidification advantages, and so on.
- On the other hand, in an economically optimized system configuration, the CHP units cover only between 10 and 40% of the electricity demand, and between 30 and 100% of the heat. This implies that the rest has to be supplied by the electricity mix and the conventional heat system. Therefore, the GHG emission reduction of around 20 to 30% in Fig. 1, for instance, is reduced to between 10 and 20% when regarded per object supplied, due to the constant base demand of peak boiler heat and electricity.

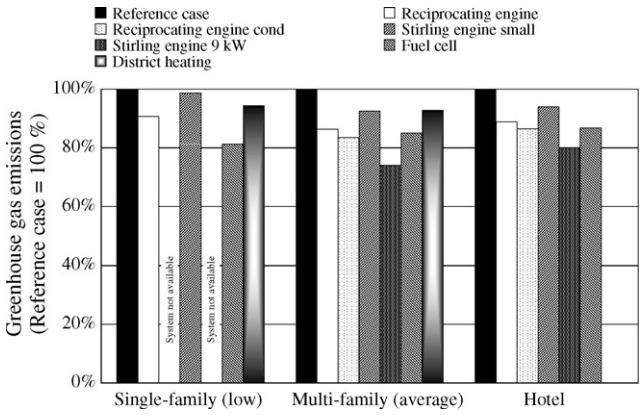

Fig. 3 – Greenhouse gas emissions of different supply objects.

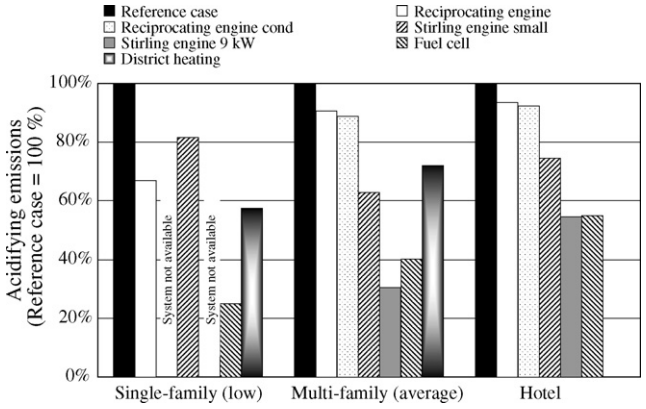

Fig. 4 – Acidifying emissions of different supply objects.

- From this perspective, the fuel cell can increase its competitive advantage particularly in the case of the *single-family house*. The reason is that these systems are limited by the prevailing heat demand. Because the fuel cell has a higher power-to-heat ratio, it produces more electricity for a given heat demand and can thus substitute higher amounts of grid electricity. The district heating system, in contrast, has rather high losses of 17.8% in the case of single-family houses (and concomitant low heat demand density).
- In the *multi-family house* connected to the district heating grid, in contrast, the heat losses drop to 2.4%; thus, the difference between district heating and micro cogeneration shrinks as well. In addition, however, district heating has a lower share of the overall heat supply.

In absolute terms, GHG reductions from 1 ton per year (single-family house) to 11 tons per year (hotel) can be achieved by operating micro cogeneration compared to the electricity mix. Carrying out the same analysis for gas combined cycle plants as suppliers of grid electricity reduces these advantages.

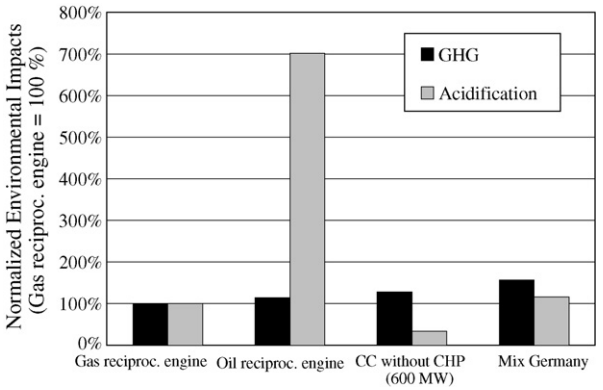

Fig. 5 – Selected life cycle impacts of micro cogeneration technologies with gas and fuel oil compared to a combined cycle (CC) plant without CHP and conventional electricity production in the year 2010. Functional unit 1 kWh electricity at low voltage level; co-produced heat is credited with a gas condensing boiler (gas reciprocating engine) and an oil condensing boiler (oil reciprocating engine).

3.5. *From gas to renewables: other micro cogeneration fuels*

In the preceding section, only natural gas as a fuel was investigated, because we believe this will be an important fuel for many European applications.

However, particularly for areas outside of larger population agglomerations, other fuels will be of high importance. Fuel oil can be more easily distributed in rural areas than gas. The picture changes further when we move to other regions worldwide. In Japan, for instance, liquefied petroleum or natural gas (LPG and LNG), fuel oil, or other fuels will be important. Also, renewable fuels can, and in the mid-term will, also be used for micro cogeneration applications.

It is not the place here to carry out a number of further LCAs. However, because of the relevance of fuel oil, it was included in a sensitivity analysis (Fig. 5). A reciprocating engine operated with fuel oil, on the one hand, combusts a fuel with higher carbon content and, hence, emits more CO_2 per MJ fuel than gas. On the other hand, the efficiency of such a unit is slightly higher (by some 2–3% points; see Table 1) than that of a gas unit. In addition, such units will not be replacing gas condensing boilers, but rather modern fuel oil heating systems.

In Fig. 5, we compare a 5.5 kW gas or fuel oil operated engine (corresponding to the Senertec Dachs) with the large non-CHP power plants from Section 3.1 ff. We observe that in terms of GHG mitigation, the oil reciprocating engine achieves almost the same level as the gas engine for the reasons given above. However, the acidifying emissions are substantially higher in the case of the oil CHP unit. This is primarily due to the much higher NO_x emissions of the fuel oil CHP unit.

When using *renewable fuels*, e.g. biogas or wood pellets, the overall GHG emissions for micro cogeneration systems will be drastically reduced. Even for rapeseed oil, the LCA will show significantly lower overall GHG emissions, despite its production requiring fossil fuel inputs and leading to further greenhouse gases due to the emission of N_2O from the agricultural system (Gärtner and Reinhardt, 2003). This positive GHG balance is, however, a general characteristic of most renewable energy systems (Pehnt et al., 2006) and not only of renewable micro cogeneration, implying that also on the side of centralized production of electricity, large CHP, or decentralized heat production without cogeneration, renewable, and thus virtually GHG-free, systems could be identified. In other words: when we discuss renewable fuels, the GHG (and energy) assessment per kWh final energy delivered will be excellent for almost all conversion systems, regardless whether they are small or large. In the context of that discussion, aspects such as technical maturity, logistical feasibility and cost are very important to keep in mind.

4. Conclusions

Most micro cogeneration systems are superior, as far as the reduction of GHG emissions is concerned, not only to average electricity and heat supply, but also to efficient and state-of-the art separate production of electricity in gas power plants

and heat in condensing boilers. This claim is the result of our Life Cycle Assessment on the technology level. It is true, despite the strong dependence of the results on the electrical and thermal efficiency of micro cogeneration technologies and further parameters such as methane emissions from reciprocating engines. Effectively, at an electrical capacity of up to five orders of magnitude smaller than large gas combined cycle power plants, lower GHG emission levels can be achieved. The GHG advantages of micro cogeneration plants are comparable to district heating with CHP.

The performance of micro cogeneration technologies with respect to climate and resource protection depends mainly on the total conversion efficiency (including the thermal output of the system) that can be achieved. In some cases, an unfavorable heat integration of micro cogeneration systems may lead to operation at the lower end of the assumed bandwidths of total efficiency. In such cases, CHP systems come rather close to electricity production in modern combined cycle plants without CHP. The optimization of micro cogeneration implementation thus involves careful integration into the supply object. Generally, the systems should not be oversized, to ensure that the full amount of heat is actually used in the system.

Under the assumption that gas condensing boilers are the competing heat-supply technology, all technologies are within a very narrow range, with the exception of the small Stirling engine, with its lower electrical and total efficiency.

Looking at the GHG reduction potential on the level of a supply object (e.g. a single-family or multi-family house), the mitigation potential is somewhat lower, because the micro cogeneration systems do not supply the whole energy demand. Rather, additional electricity from the grid and heat from a peak boiler have to be taken into consideration. Here, fuel cells offer the advantage of a higher power-to-heat ratio, implying that, for a given heat demand, more electricity can be generated that displaces conventionally produced electricity.

Environmental impacts other than those related to climate and resource protection relate more specifically to technology. Whereas for fuel cells and Stirling engines (as long as these use innovative flameless burner technologies) emissions of air pollutants are extremely low, reciprocating engines emit more significant amounts of NO_x, CO, and hydrocarbons. Furthermore, the emission factors of reciprocating engines depend heavily on operation characteristics, age and maintenance of the systems. Thus, larger bandwidths characterize this system. As a consequence, acidifying emissions of small reciprocating engines (considering the heat co-product) are somewhat higher than those of centralized gas power plants, due to more efficient emission control in the latter. The environmental analysis must be complemented by an economic assessment. Generally, under current energy political circumstances, micro cogeneration proves to be economically successful compared to non-CHP heat and electricity production in those countries with a favorable regulatory framework (e.g. tax exemptions or feed-in tariffs such as in Germany). The economic and environmental performance must then be compared to other energy-efficient and climate friendly supply systems, such as larger district heating systems or solar collectors coupled to gas condensing boilers.

In addition to investigating the emissions side, analysis of the concentration of pollutants in a residential area supplied by reciprocating engines was carried out. The analysis shows that for selected, rather unfavorable, meteorological conditions, with a flat topography and urban housing structure, the additional level of NO_x due to the engines is below the value of significance according to German legislation, and does not create severe additional environmental impacts.

When interpreting the overall environmental achievements of micro cogeneration, it has to be kept in mind that, as long as the fuels for micro cogeneration units are based on fossil resources, greenhouse gases are emitted and finite energy resources used. Therefore, it is necessary to embed the use of micro cogeneration units into a strategy of renewable energy carriers, energy efficiency, and energy saving.

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Martin Pehnt studied Physics and Energy Management in Tübingen, Stuttgart, Berlin and Boulder (USA) and obtained a Masters Degree in 1996 and a PhD in Energy Technology in 2002. Research period at the National Renewable Energy Laboratory NREL (Golden, Colorado). 1997–2001 Scientist at the German Aerospace Center, Institute for Technical Thermodynamics, Department for Systems Analysis and Technology Assessment. Since 2001 Senior Scientist at the Institut für Energie- und Umweltforschung Heidelberg IFEU. Expert consultant for the German Federal Environmental Ministry. His research focuses on technology and environmental assessment of innovative energy and transport systems, such as fuel cells, cogeneration, renewable energies, bio fuels; environmental communication.